Measurement of Optical Properties and Thermal Performance of Coloured Thin Layer Asphalt Samples and Evaluation of Their Impact on The Urban Environment

Afroditi Synnefa*, Theoni Karlessi, Niki Gaitani, Mat Santamouris,
Group Building Environmental Studies, National and Kapodistrian University of Athens,
Department of Applied Physics, Physics Department, Greece
C. Papakatsikas
Aktis S.A, Thessaloniki, Greece
*Corresponding author email: asynnefa@phys.uoa.gr

ABSTRACT

This paper presents the results of study aiming to measure solar spectral properties and the thermal performance of 5 (green, red, yellow, beige and off-white) color thin layer asphalt samples in comparison to a sample of conventional black asphalt. In addition the impact of the application of such materials on pavements (road) on surface and air temperature is evaluated. These materials can be applied on new or existing asphalt pavements that are in good condition. This study consists of three parts a) Spectral analysis and study of the optical properties of the samples b) Study and analysis of the thermal performance of the samples. c) Computational fluid dynamics (CFD) simulation for evaluating the impact of applying the samples in outdoor spaces.

The spectrophotometric measurements showed that the coloured thin layer asphalt samples are characterised by higher values of solar reflectance compared to the conventional asphalt, which is mainly due to their high near infrared solar reflectance. From the statistical analysis of the surface temperatures it was found that all the colored thin layer asphalt samples demonstrate lower surface temperatures compared to conventional asphalt. The maximum temperature difference recorded was for the off-white sample and was equal to 12 $^{\circ}$C. The CFD simulation results show that both surface and air temperatures are decreased when applying the colour thin layer sample.

Introduction

The urban microclimate is mainly influenced by increased building density with the canyon geometry, the use of materials with inappropriate optical and thermal properties and the lack of green spaces, increased anthropogenic heat and increased air pollution (Oke et al., 1991, Santamouris 2001). The Urban Heat Island (UHI) effect, with temperatures in urban areas higher by several degrees compared to the surrounding rural areas, has been documented in over 30 cities worldwide (LBNL Heat Island Group, Santamouris 2007, Kataoka et al., 2009). The UHI has the effect of increasing the demand of energy and energy prices, accelerating the formation of harmful smog and causing human thermal discomfort and health problems by intensifying heat waves over cities (Clarke 1972, Oke et al., 1991; Akbari et al.,1992; Hassid et al., 2000; Santamouris, 2001; Cartalis et al., 2001; Stathopoulou et al., 2005).

The surface temperature is of prime importance as it modulates the air temperature of the lowest layers of the urban atmosphere, it is central to the energy balance of the surface, helps to determine the internal climates of buildings and affects the energy exchanges that affect the comfort of city dwellers (Voogt and Oke, 2003). Pavements (roads, parking spaces etc.) cover an

important percentage of a city's surface and their thermal characteristics play a dominant role in the formation of the urban heat island effect. Paved surfaces contribute to sunlight's heating of the air near the surface and they can transfer heat downward to be stored in the pavement subsurface, where it is re-released as heat at night (Pomerantz et al. 2000a, EPA 2009a). Asaeda et al., 1996 found that pavement heat flux in Tokyo is equal to about half the energy consumption rate of the city. Conventional pavements are usually impervious made of concrete and asphalt, with solar reflectance values ranging between approximately 4% and 45% (Stathopoulou et al. 2009, EPA2009a), which can reach peak summertime surface temperatures of 48–67°C (EPA 2009a, Santamouris 2001, Doulos 2001).

One of the heat island mitigation strategies that has been proposed by researchers and has gained a lot of interest in the last years is the use of cool materials (for building envelopes and pavements). Cool materials are characterized by high solar reflectance and infrared emittance values. These two properties result in lower surface temperatures. If the surface is on the building envelope, the heat penetrating into the building will be decreased, if it is any surface of the urban environment it will contribute to decrease the temperature of the ambient air as the heat convection intensity from a cooler surface is lower (Bretz and Akbari, 1997).

Cool roofing products are made of highly reflective and emissive materials, are usually bright white and can remain approximately up to 30°C cooler than traditional materials during peak summer conditions (EPA 2009b, Synnefa et al., 2006). Researchers and manufacturers, have also been developing cool colored roofing materials for the cases where the use of light colors creates glare problems or when the aesthetics of darker colors is preferred (Levinson et al. 2007a, Levinson et al. 2007b Synnefa et al. 2007). The Cool roofs technology and market is well established with measurement standards related to Cool Roof products (e.g. those by ASTM reported in EPA2009b), organizations rating and promoting cool roof products (Energy Star, Cool Roofs Rating Council, LBNL, EPA, EU Cool roofs project) and energy codes including them.

Unlike cool roofing materials, cool paving materials technology is still under development, no official standards or definitions exist and more research in this field is required (EPA2009a). Cool pavements refer to a range of established and emerging materials that tend to store less heat and may have lower surface temperatures compared with conventional products (EPA 2009a). As reported in Cambridge Systematics, Inc. (2005), possible mechanisms for creating a cool pavement that have been studied to date are a) increased surface reflectance, which reduces the solar radiation absorbed by the pavement; b) increased permeability, which cools the pavement through evaporation of water; and c) a composite structure for noise reduction, which also has been found to emit lower levels of heat at night. This paper focuses on the first mechanism.

Increasing the solar reflectance of a paved surface keeps it cooler under the sun, reducing convection of heat from pavement to air and also thereby decreasing the ambient air temperature. Lower air temperatures decrease demand for cooling energy and slow the formation of urban smog. Measured data reported by Akbari et al., 2001, clearly indicate that increasing the pavements' solar reflectance by 0.25 causes significant decrease of the pavement temperature by 10°C. Simulations of the influence of pavement albedo on air temperature in Los Angeles predict that increasing the albedo of 1250 km^2 of pavement by 0.25 could potentially reduce air temperature by 0.6°C, which would result in significant benefits in terms of lower energy use and reduced ozone levels. More specifically, it would result in cooling energy savings worth $15 million per year, and smog-related medical and lost-work expenses reduction by $76 million year^{-1} (Rosenfeld et al. 1998, Taha 1997). Many studies report the combined effect of increasing the albedo of both roofs and pavements, which can reduce the summertime urban temperature

and improve the urban air quality (Taha 2002; Taha 2001; Taha et al. 2000; Rosenfeld et al. 1998; Akbari et al. 2001). In addition, increasing urban albedo can result in less absorption of incoming solar radiation by the surface-troposphere system, countering to some extent the global scale effects of increasing greenhouse gas concentrations. It has been estimated that increasing pavement albedo in cities worldwide by 0.15, could achieve reductions in global carbon dioxide (CO_2) emissions equivalent to 20 Gt, worth about $500 billion (Akbari et al., 2009).

In addition to reduced air temperatures, energy use and air quality benefits, it has been shown, that reduced pavement surface temperatures can result in increasing the useful life (durability) of pavements and reduce waste from maintenance. Furthermore, reflective pavements can enhance visibility at night, potentially reducing lighting requirements and saving money and energy (Pomerantz et al. 2000b).

A potential drawback from raising the solar reflectance of pavements is that it could create glare problems, when driving for example, reducing also visibility of the white line; or it may not be appropriate in places where people will be uncomfortably exposed to the reflected radiation for long periods, as in a children's playground. In order to avoid these problems, Kinouchi et al. (2004) have developed a new type of pavement that satisfies both high albedo and low brightness based on the application of an innovative paint coating on conventional asphalt pavement. The pigments and coating structure used are effective in achieving low reflectivity in the visible part of the spectrum (23%) and high near-infrared reflectivity (86%). Field measurements show that the maximum surface temperature of the paint-coated asphalt pavement is about 15°C lower than that of the conventional asphalt pavement.

In this paper we report our work on five different colored thin layer asphalt samples that we developed and can be applied over new or existing asphalt pavements in good condition, in order to increase solar reflectance but maintaining a dark color. This study reports the results of the spectral analysis based on the measured optical properties of the samples, the analysis of the thermal performance of the samples under summer weather conditions and the evaluation of the impact of applying the samples in outdoor spaces using a computational fluid dynamics model.

Experimental procedure

In the framework of this study five (green, red, yellow, beige and off-white) color thin layer asphalt samples have been developed by an industrial partner of the University of Athens and were submitted for testing. The color thin layer asphalt samples were developed by mixing an elastomeric asphalt binder (colorless) and adding special pigments and aggregates of special sizes and colors. The tested samples are shown in Figure 1. In addition, a sample of conventional black asphalt was also tested and used as reference. For the testing, the asphalt samples have been applied on asphalt membranes at a thickness of 0.5 cm. The dimensions of the samples were 33 cm x 33 cm for the temperature measurements.

In order to study the optical properties and the thermal performance of the coatings the following parameters were measured:
(a) The spectral reflectances of the samples. These were measured using a UV/VIS/NIR spectrophotometer (Varian Carry 5000) fitted with a 150 mm diameter, integrating sphere (Labsphere DRA 2500) that collects both specular and diffuse radiation. The reference standard reflectance material used for the measurement was a PTFE plate (Labsphere). Spectral reflectance measurements were performed according to ASTM E903-96: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres.

Figure 1. The five (1. beige, 2. off-white, 3. green, 4. red, 5. yellow) tested color thin layer asphalt samples
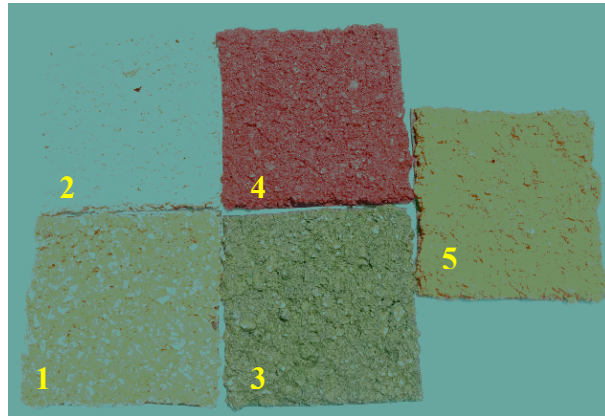
(b) The surface temperature of the samples on a 24 h basis. The basic experimental equipment consists of surface temperature sensors (thermocouples type K) connected to a data logging system. Instantaneous values were measured and saved on a computer hard disc every 15 min. The temperature sensors were placed on the centers of the surfaces of each tile. An infrared camera (AGEMA Thermovision 570, 7.5– 13 μm wavelength) was also used to depict the temperature differences between samples.

For the testing of their thermal performance the samples were placed on a specially modulated platform covering a surface of 20 m^2. The platform was horizontal, unshaded during the whole day and insulated from below in order to eliminate the heat transfer effects between the platform and the samples. The experimental procedure took place during the month of July 2008.

Measurements of the ambient meteorological conditions, recorded from a meteorological station near the experimental site, include ambient temperature, relative humidity, wind speed, global and diffuse solar radiation on a horizontal surface and have been used to characterize the outdoor climatic conditions. The ambient temperature, the relative humidity, the monthly average daily diffuse and global solar radiation (W/m2) on a horizontal surface during the experimental period are described in Table 1.

Table 1: Ambient meteorological conditions during the experimental period (Source: National Observatory of Athens)

Time	Air temperature (°C)			Relative Humidity (%)	Wind speed (m/sec)	Monthly average daily diffuse solar radiationα (W/m^2)	Monthly average daily global solar Radiation (W/m^2)
	Mean	Max	Min				
1st – 31st July 2008	28.7	39.3	20.5	44	3.7	5.3	7958

Analysis of the measured spectral optical properties of the tested samples

The results from the spectrophotometric measurements are shown in Figure 2. Spectral reflectance data were used to calculate the solar reflectance of each sample. The calculation was carried out by weighted-averaging, using a standard solar spectrum as the weighting function. The spectrum employed is that provided by ASTM (see standards ASTM E903-96 and ASTM G159-98). Additionally, the solar reflectance values for the ultra violet (UV, 300-400nm), visible (VIS, 400-700nm), and near –infrared (NIR, 700-2500nm) part of the spectrum were calculated. These values for each sample are shown in Table 2.

The reflectance of the color thin layer asphalt samples was found to be higher than the reflectance of the conventional black asphalt in all the cases as it appears in Table 2 and Figure 3. The solar reflectance of the samples ranges between 0.27 (red and green samples) and 0.55 (off-white sample), and the solar reflectance of the conventional black asphalt is 0.04 (or 4%). Furthermore, all the samples present quite high absorptance in the UV (300-400nm), ranging from 0.90 to 0.96 (Figure 2 and Table 2).

In the visible part of the spectrum, the reflectance depends on the specific color. The highest visible reflectance was measured for the off-white colored sample (0.45) and the lowest for the black conventional asphalt (0.03).

As shown in Table 2 and Figure 2, all the color thin layer asphalt samples demonstrate quite high reflectance values in the near infrared part of the spectrum, ranging from 0.39 to 0.56. For all the samples the NIR solar reflectance is significantly higher compared to the visible reflectance. Even the dark colored samples (low visible reflectance), have high near infrared reflectance. For example, the green thin layer asphalt sample is characterized by a very low visible reflectance (0.10), its near infrared reflectance reaches 0.39. On the contrary, the conventional black asphalt sample demonstrates very low visible reflectance (0.03) and also very low near infrared reflectance equal to 0.04.

Table 2: Solar reflectance values (SR, 300-2500nm) and solar reflectance values in the UV (300-400nm), VIS (400-700nm) and NIR (700-2500nm) part of the spectrum of the five tested samples and the sample of conventional black asphalt

Sample	SR	SR_{UV}	SR_{VIS}	SR_{NIR}
Beige thin layer asphalt	45	10	31	56
Off-white thin layer asphalt	55	10	45	63
Green thin layer asphalt	27	8	10	39
Red thin layer asphalt	27	6	11	40
Yellow thin layer asphalt	40	8	26	51
Conventional black asphalt	4	4	3	4

This high near infrared "invisible" reflectance, explains the fact that the color thin layer asphalt samples are characterized by high solar reflectance values. This is because although sunlight is more intense in the visible range, it also emits a substantial amount of energy in the invisible ultraviolet (UV) and near-infrared (NIR). In fact, about half of all solar power arrives as invisible near-infrared radiation.

Figure 2. The five (A. beige, B. off-white, C. green, D. red, E. yellow) tested color thin layer asphalt samples and the conventional black asphalt (F)
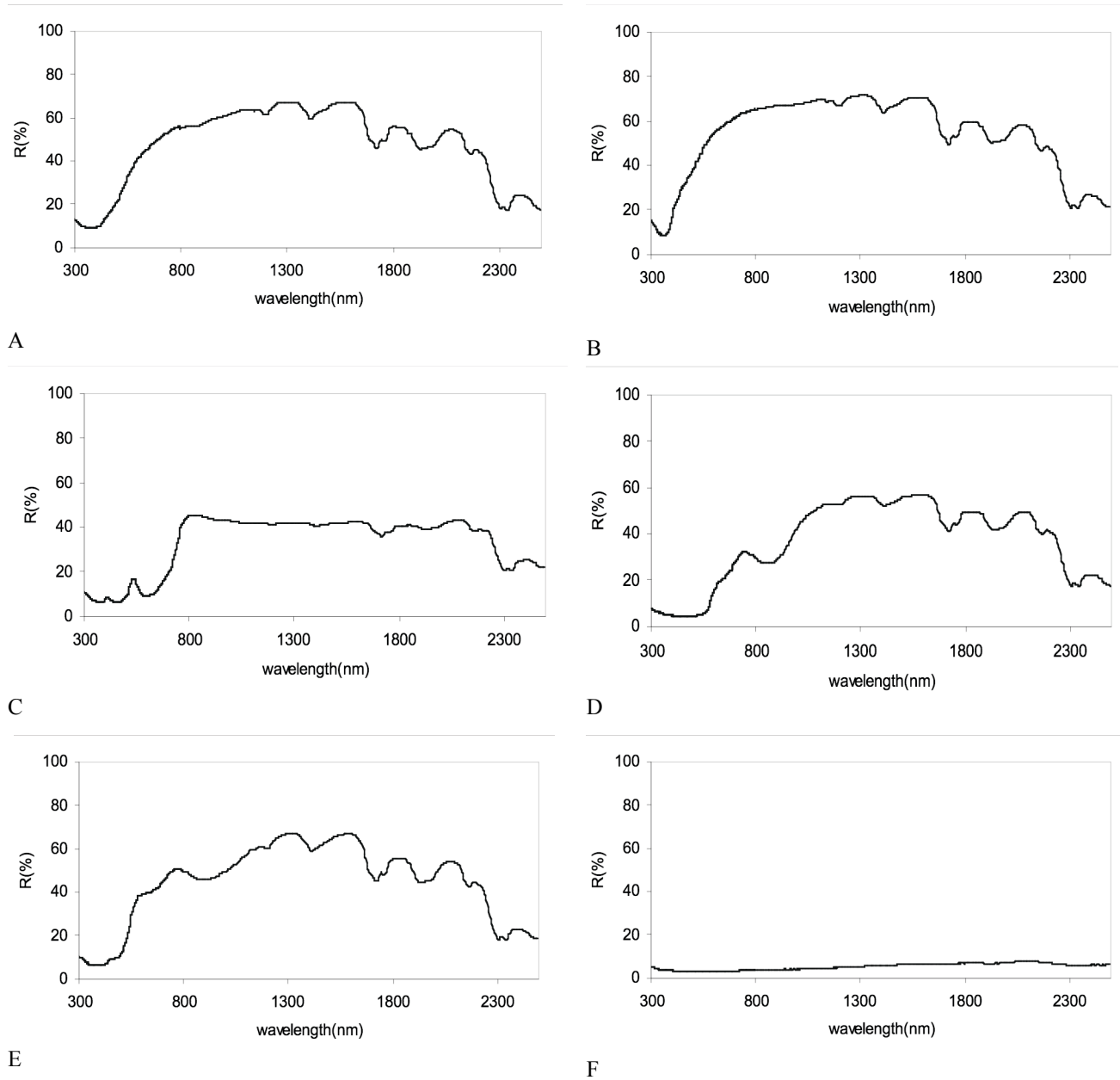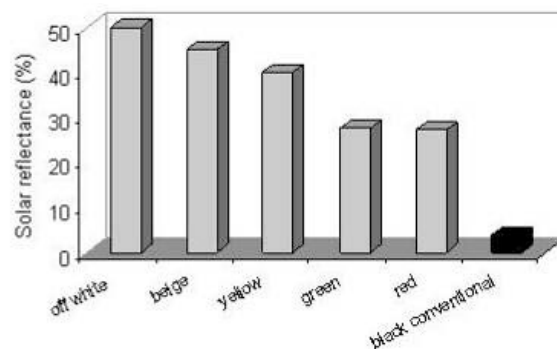

A

B

C

D

E

F

Figure 3. The solar reflectance of the five tested color thin layer asphalt samples and the conventional black asphalt.

Study and analysis of the thermal performance of the samples

Based on the surface temperature measurements, the mean daily surface temperature (07:00-19:00 LST) and the mean nocturnal surface temperature (00:00-07:00 and 19:00-00:00) were calculated for each sample. The results of the calculations are shown in Table 3. The mean and mean max surface temperature difference between the conventional black asphalt and the five color thin layer asphalt samples are also shown in Table 3.

Table 3: Mean and mean maximum daily and nocturnal surface temperature of the tested samples during the experimental period.

Sample	Surface Temperature (^{o}C)				
	Daily				Nocturnal
	mean	ΔT_{mean}	Mean max	ΔT_{max}	mean
Black conventional	**46.7**	**-**	**59.9**	**-**	**21.6**
Off-white	39	7.7	48	11.9	21.1
Yellow	40	6.7	50.7	9.2	19.4
Beige	40.5	6.2	52	7.9	19.1
Red	43.6	3.1	55.8	4.1	20.7
Green	43.5	3.2	55.1	4.8	19.7

Figure 4 shows the 24h distribution of the mean hourly surface temperatures of the tested samples during the experimental period. Mean hourly values of the ambient air temperature are also depicted.

During the day all the samples demonstrate surface temperatures that were higher than the ambient air temperature. During the night the air temperature is always higher than the surface temperature of the tested samples. This is because all the samples are characterised by high values of emissivity and thus have the ability to release faster the heat they have absorbed due to night sky radiative cooling.

Figure 4: 24h distribution of the mean hourly surface temperatures of the tested samples and air temperature during the experimental period (July 2008)
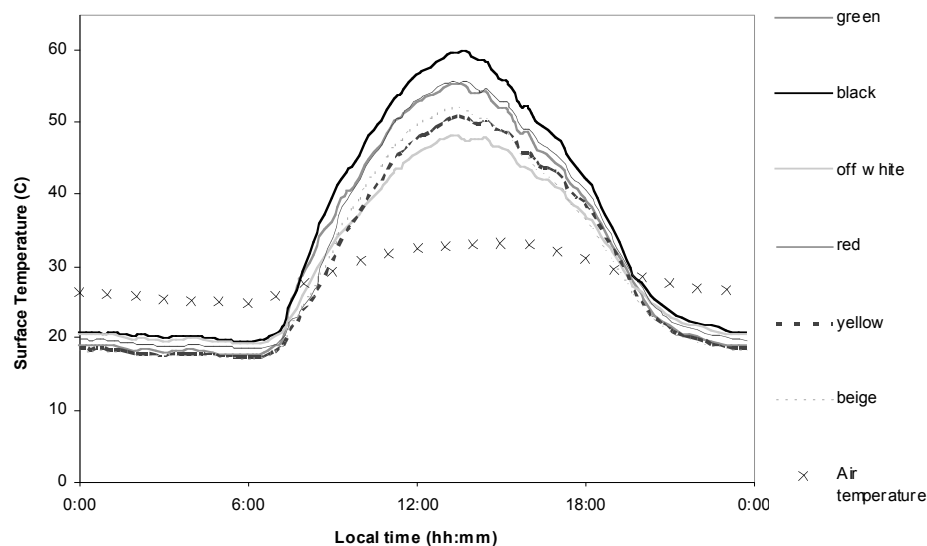
As is shown in Table 3 and Figure 4, all the 5 colored thin layer asphalt samples demonstrate lower surface temperatures compared to the black conventional asphalt. The mean daily temperature of the color thin layer samples ranges from $39^{\circ}C$ for the off-white asphalt sample to $43.6^{\circ}C$ for the red sample. The corresponding temperature for the black conventional asphalt sample is $46.7\ ^{\circ}C$. The mean max daily surface temperature of the colored thin layer samples ranges from $48^{\circ}C$ for the off-white asphalt sample to $55.8^{\circ}C$ for the red sample. The corresponding temperature for the black conventional asphalt sample is $60\ ^{\circ}C$. It can be concluded that the red sample has a max surface temperature that is by 7% lower compared to the surface temperature of the black conventional asphalt, the green sample by 8%, the beige and yellow by 13% and 15% respectively, and the greatest difference was recorded for the off-white sample that equals 20%. These temperature differences between the samples can be explained if we take into account the solar reflectance values of the samples. The higher the solar reflectance, the lower the surface temperature, as less solar radiation is absorbed by the sample.

Infrared thermography was used to investigate the temperature distribution of the samples and to depict the differences in their thermal performance. Figure 5 represents a visible and an infrared image of the six tested coatings. It was found that the sample temperatures were quite uniform. The visible and IR photos were taken during peak surface temperature time and for a hot summer day. As expected the black conventional asphalt sample that presents the lowest solar reflectance (0.04), appears as the hottest, followed by the red (SR=0.27), the green (SR=0.27), the yellow (SR=0.40) and the beige (SR=0.45). The off-white thin layer asphalt sample with the highest solar reflectance (0.55) appears to have the lowest temperature.

Figure 5: Visible (A) and infrared (B) images of the five color thin layer asphalt samples and black conventional asphalt sample: 1. off-white, 2. yellow, 3. green, 4. black (conventional) 5.beige, 6. red
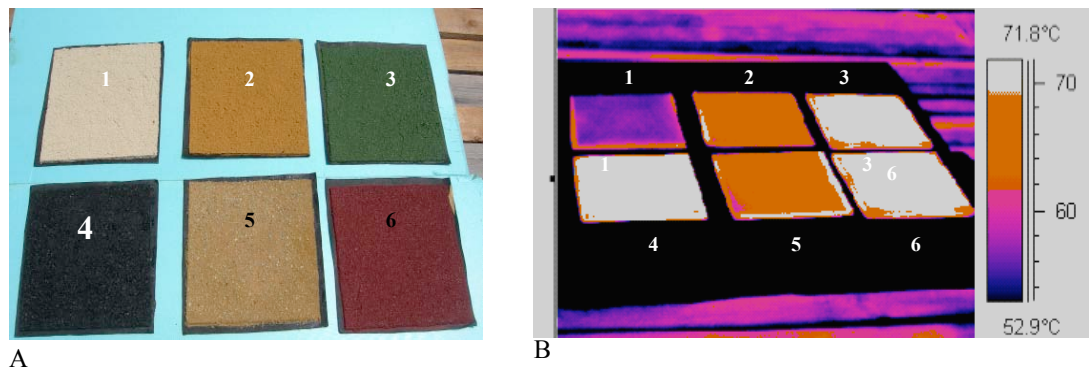

Evaluation of the impact of applying the samples in outdoor spaces

A computational fluid dynamics model has been used in order to investigate the impact on air temperatures at local scale between a base case where conventional asphalt was used and another case using the off –white (SR=0.55) sample. The evaluation of the current as well as the proposed situation after the application of the examined cool material for microclimatic modification was achieved with the use of PHOENICS CFD (http://www.cham.co.uk/) model.

The simulation was performed for a main, commercial road (Ag. Ioannou st.) situated in the suburbs of Athens (Figure 6A), surrounded mainly by residential area.

There are 4-5 story buildings adjacent to the road. The grid of the calculation domain has dimensions of 1380(x)*1704(y)*150(z) m and consist of 80x140x50 cells at each axis respectively. Simulations were performed for the summer period and for a north wind of 2m/sec and the measured surface temperatures of the samples have been taken into account. For the ambient meteorological conditions data from the National Observatory of Athens have been used.

**Figure 6: Satellite image (A) , geometry and calculation domain (B) of the simulated area**

A

B
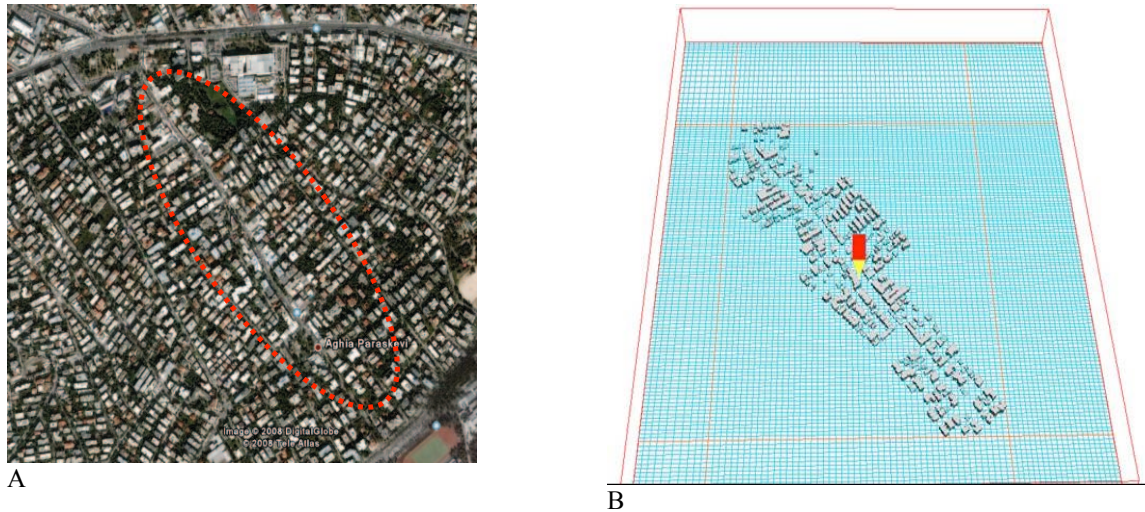
According to the results of the simulations for the case where the conventional black asphalt (SR=0.04 and maximum surface temperature 60°C) is applied on the road, the air temperature at 1.5 m height, ranged between 37°C and 47°C (average 42°C). For the second case, where the off-white thin layer asphalt (SR=0.55 and maximum surface temperature 45°C) was applied on the road, the air temperature at 1.5m height, ranged between 36°C and 41°C (average 37°C).

Figure 7 describes the air temperature field at 1.5m height for the simulated area for the case of the black asphalt (A) and for the case of the off-white thin layer asphalt (B).

Comparing the results of the first and second case it can be concluded that the application of the off-white thin layer asphalt on the road, resulted in a significant air temperature reduction in the simulated area equal to 5°C on average.

Figure 7: The air temperature field at 1.5m height for the simulated area for the case of the black asphalt (SR=0.04)(A) and for the off-white thin layer asphalt (SR=0.55)(B).
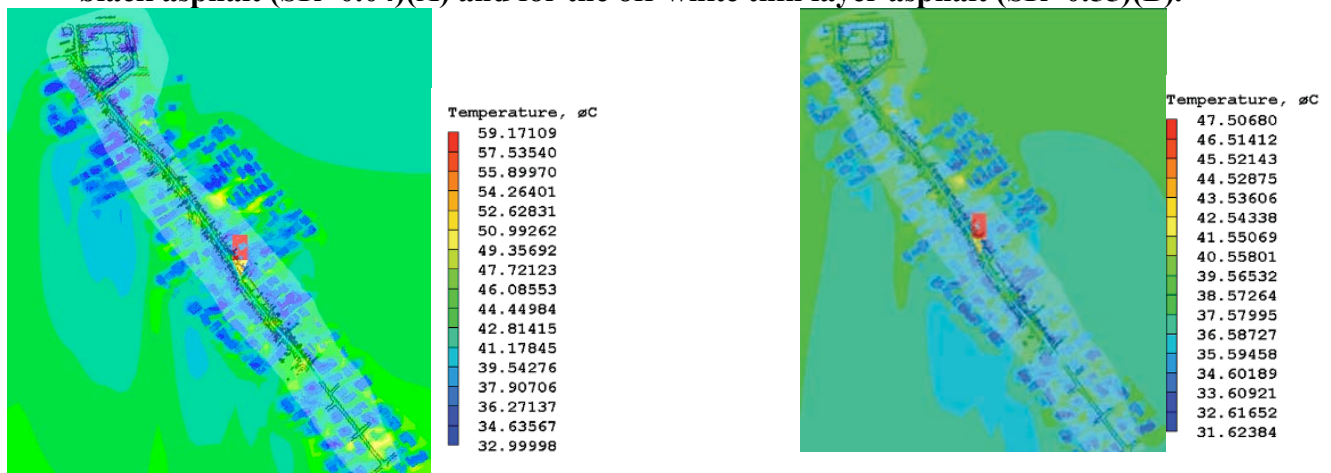
Conclusions

Five coloured thin layer asphalt samples that can be applied on existing and new asphalt pavements have been developed and tested in order to evaluate their optical and thermal performance. It was found that all the samples demonstrated higher solar reflectance values and lower surface temperatures compared to conventional black asphalt. CFD simulations showed that replacing conventional asphalt in a road could lead to an average air temperature decrease of 5°C. The results of this study indicate that the use of color thin layer asphalt in roads and pavements can have significant impact in lowering surface and air temperatures, mitigating thus the heat island effect and its consequences. It should be pointed out that although cool pavement technologies like the one investigated in this paper are already available, local governmental agencies lack the information and incentives to apply these in a coordinated and consistent way throughout city areas. It is important to create a strategic plan to promote cool pavements including measurement standards, defined rating and evaluation procedures and financial incentives and policies for their application.

References

Akbari H., Menon S. and Rosenfeld A. (2009), Global cooling: increasing world-wide urban albedos to offset CO_2, Climatic Change (2009) 94:275–286, DOI 10.1007/s10584-008-9515-9.

Akbari H., Pomerantz M., and Taha H., (2001), Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas, Solar Energy 70, Issue 3, pp. 295-310

Akbari, H., Davis, S., Dorsano, S., Huang, J., Winert, S., 1992. Cooling our Communities—A Guidebook on Tree Planting and White Coloured Surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division

Asaeda, T., Ca, V.T., Wake, A., 1996. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 30 (3), 413–427.

Bretz, S., Akbari, H., 1997. Long-term performance of high albedo roof coatings. Energy and Buildings 25, 159–167.

Cambridge Systematics, Inc. (2005), Cool Pavements Draft Report. Available on line at: http://www.epa.gov/hiri/resources/pdf/CoolPavementReport_Former%20Guide_complete.pdf

Cartalis, C., Synodinou, A., Proedrou, M., Tsangrasoulis, A., Santamouris, M., 2001. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the Southeast Mediterranean region. Energy Conversion and Management 42 (14), 1647–1656.

Clarke J. F., 1972, Some effects of the urban structure on heat mortality. Environmental Research Volume 5, Issue 1, March 1972, Pages 93-104. doi:10.1016/0013-9351(72)90023-0

Cool Roof Rating Council: http://www.coolroofs.org/

Doulos, L., Santamouris, M., Livada, I., 2004. Passive cooling of outdoor urban spaces. The role of materials. Solar Energy 77, 231–249.

Energy Star Roof products: http://www.energystar.gov/index.cfm?c=roof_prods.pr_roof_products

EPA: US Environmental Protection Agency: http://www.epa.gov/hiri/mitigation/index.htm

EPA 2009a, Reducing Urban Heat Islands: Compendium of Strategies Cool Pavements, Available on line at: http://www.epa.gov/hiri/resources/compendium.htm

EPA 2009b, Reducing Urban Heat Islands: Compendium of Strategies Cool roofs, Available on line at: http://www.epa.gov/hiri/resources/compendium.htm

EU Cool Roofs project web site: http://www.coolroofs-eu.eu/

Hassid, S., Santamouris, M., Papanikolaou, N., Linardi, A., Klitsikas, N., Georgakis, C., Assimakopoulos, D.N., 2000. The effect of the Athens heat island on air conditioning load. Energy and Buildings 32, 131–141.

Kataokaa K., Matsumotob F., Ichinoseb T., Taniguchic M. (2009), Urban warming trends in several large Asian cities over the last 100 years, Science of The Total Environment, Vol.407, Issue 9, pp. 3112-3119. doi:10.1016/j.scitotenv.2008.09.015

LBNL Heat Island Group: http://heatisland.lbl.gov/

Levinson R., Akbari H., Reilly J.C (2007a). Cooler tile-roofed buildings with near-infrared-reflective non-white coatings. Building and Environment, 42 (7), pp. 2591-2605.

Levinson R., Berdahl P., Akbari H., Miller W., Joedicke I., Reilly J., Suzuki Y., Vondran M. (2007b), Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials, Solar Energy Materials and Solar Cells, 91 (4), pp. 304-314.

Oke, T.R., D.G. Johnson, D.G. Steyn, and I.D. Watson, 1991: Simulation of surface urban heat island under 'ideal' conditions at night – Part 2 : Diagnosis and Causation. Bound.- Layer Meteor., 56, 339-358

Pomerantz M., Pon B., Akbari H., and Chang S.C. (2000a). The Effect of Pavements' Temperatures On Air Temperatures in Large Cities. LBNL Report-43442

Pomerantz, M., H. Akbari, and J. T. Harvey. (2000b). The benefits of cooler pavements on durability and visibility. Lawrence Berkeley National Laboratory Report No. LBNL-43443, Berkeley, CA

Rosenfeld A.H., Akbari H., Romm J.J. and Pomerantz M., Cool communities: strategies for heat island mitigation and smog reduction. Energy Build. 28 1 (1998), pp. 51–62.

Santamouris, M., 2007. *Heat island research in Europe - State of the art.* Advances Building Energy Research 1. pp. 123-150

Santamouris, M. (Ed.), 2001. Energy and Climate in the Urban Built Environment. James and James Science Publishers, London.

Stathopoulou M, Synnefa A., Cartalis C., Santamouris S, Karlessi T., and Akbari H. (2009), A surface heat island study of Athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials, International Journal of Sustainable Energy,28:1,59 — 76.

Stathopoulou, M., Cartalis, C., Andritsos, A., 2005. Assessing the thermal environment of major cities in Greece. In: Proc. 1st International Conference on Passive and Low Energy Cooling for the Built Environment, Santorini, Greece.

Synnefa A., Santamouris M., and K. Apostolakis, 2007: On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Sol. Energy, 81, 488–497

Synnefa, A., Santamouris, M., Livada, I., 2006. A study of the thermal performance and of reflective coatings for the urban environment. Solar Energy 80, 968–981.

Taha, H. 2002. "Meteorological and Air Quality Impacts of Increased Urban Surface Albedo and Vegetative Cover in the Greater Toronto Area, Canada." Lawrence Berkeley National Laboratory Report No. LBNL-49210, Berkeley, CA.

Taha, H. 2001. "Potential Impacts of Climate Change on Tropospheric Ozone in California: A Preliminary Episodic Modeling Assessment of the Los Angeles Basin and the Sacramento Valley." Lawrence Berkeley National Laboratory Report No. LBNL-46695, Berkeley, CA.

Taha, H., S.-C. Chang and H. Akbari. 2000. "Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three U.S. Cities."Lawrence Berkeley National Laboratory Report No. LBL-44222, Berkeley, CA.

Taha, 1997 H. Taha, Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin, Atmospheric Environment 31 (11) (1997), pp. 1667–1676

Voogt J A, Oke T R, 2003. Thermal remote sensing of urban climates[J]. Remote Sens Environ, 86: 37Ck-384.